Multifunctional Poro-Vascular Composites for UAV Performance Enhancement

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Outline

- Introduction & UAV Application
- Functional Overview
- Fluid-Phase Modeling
- Electro-Wetting Phenomena
- Fabrication & Vascular Flow Control
- Summary

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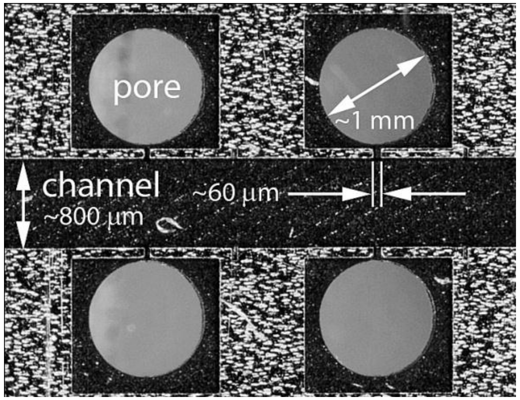
Poro-Vascular Composites

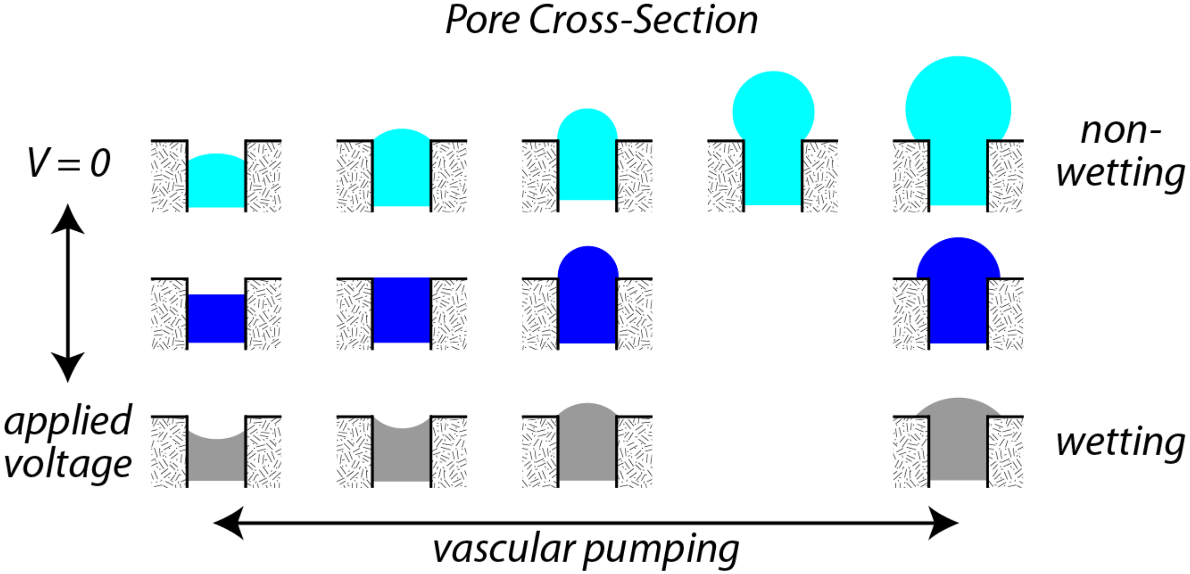
Multifunctional structural "skin" materials with surface pores and internal vascular channels filled with an ionic-liquid whose height and shape at the pore exits is actively controlled.

Key Features

- Flexible structural skin laminate with *t* ~ mm.
- Surface-roughness control on sub-mm scale.
- Structure-roughness multifunctionality.

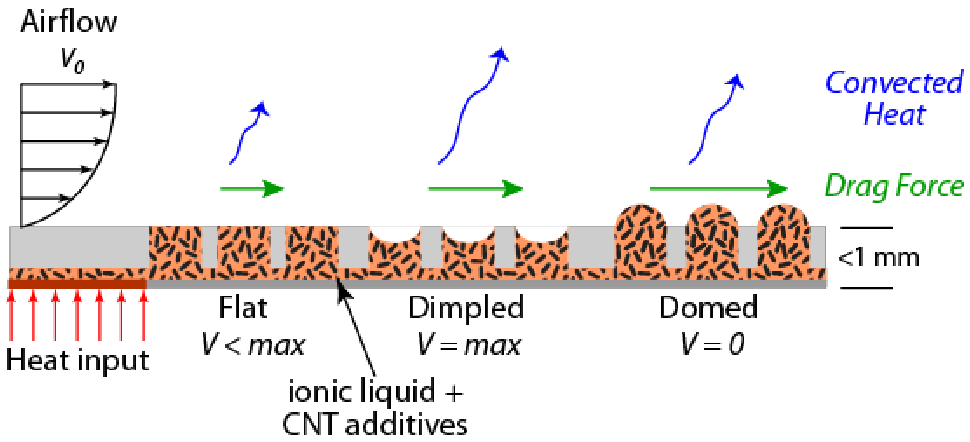


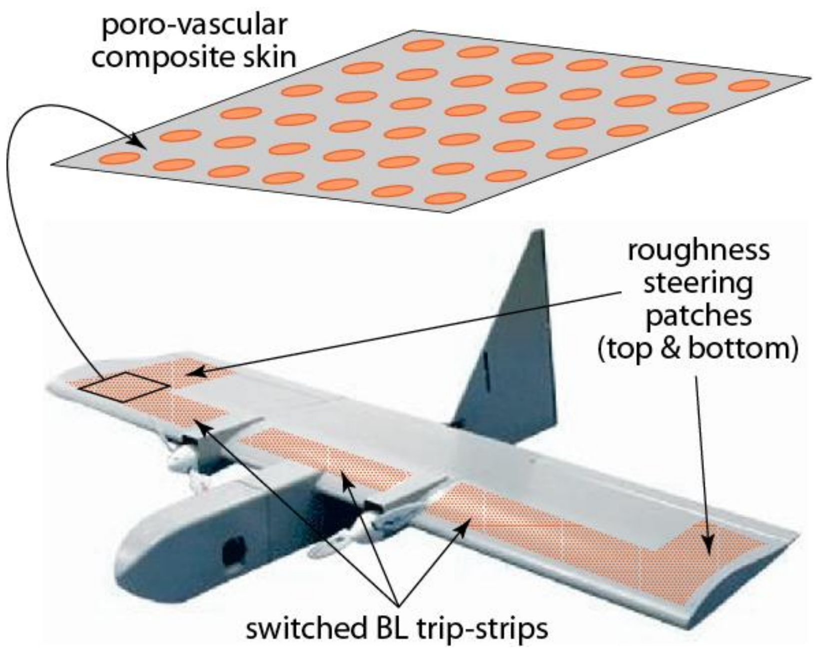
Fluid-Phase Surface Morphologies



UAV Applications

Structural skin layer with active surface roughness control for drag/heat transfer tuning → enhanced performance & energy efficiency.





Surface Roughness Effects

Surface Configuration	Normalized Heat Transfer, St/St_o	Normalized Skin Friction, C_f/C_{fo}
Flat	1.0	1.0
Dimpled	1.3-1.6	1.2-2.2
Domed	1.4-2.5	2.5-3.3

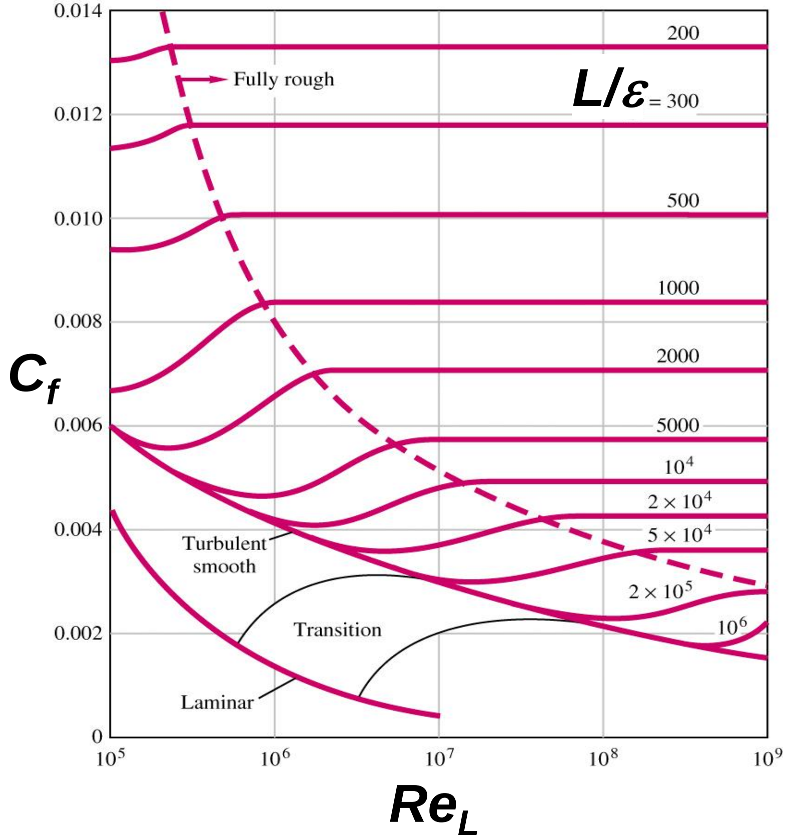
Reference: Kithcart, M.E. & Klett, D.E., *J Enhanced Heat Transfer*, 3(4), 1996.

Aerodynamic Notions

profile drag **drag due to lift**

Total Drag = (skin-friction + pressure) drag + induced drag

Skin-friction drag (C_f) versus Reynold's number (Re_L)
for Flat Plates with Surface Roughness (ε/L)



Reference: www.hpcnet.org/upload/directory/.../15698_20080506135629.ppt

Surface Roughness Effects

Increased roughness (ε/L) →

- no effect on C_f in laminar flow regime,
- significant increase in C_f in turbulent regime,
- transitions to turbulent boundary-layer flow at lower *Re*.

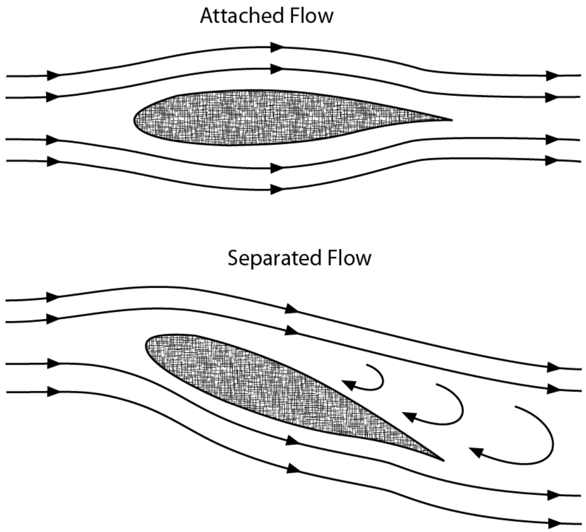
Aerodynamics Notions (cont'd)

profile drag — **drag due to lift**

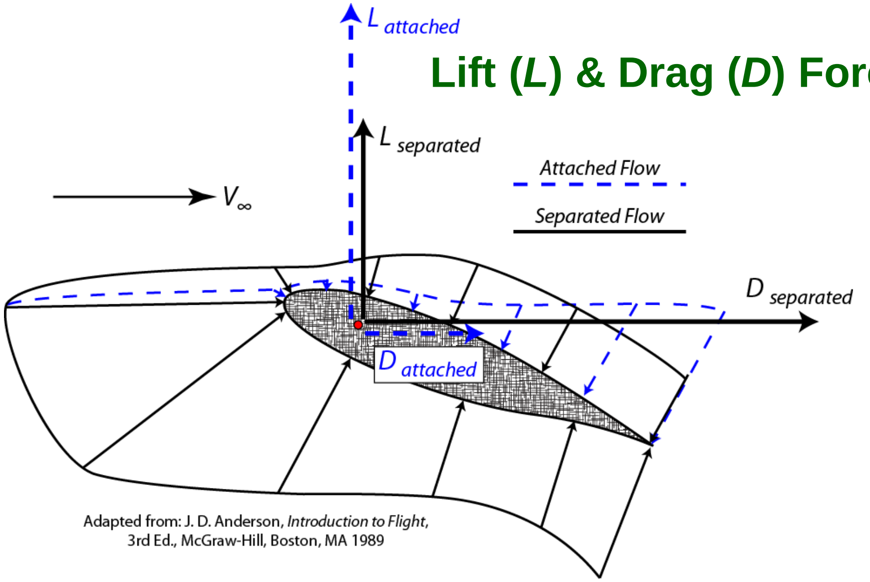
Total Drag = (skin-friction + pressure) drag + induced drag

Pressure drag affected by boundary-layer flow separation!

Airfoil Boundary-Layer Separation



Lift (L) & Drag (D) Forces



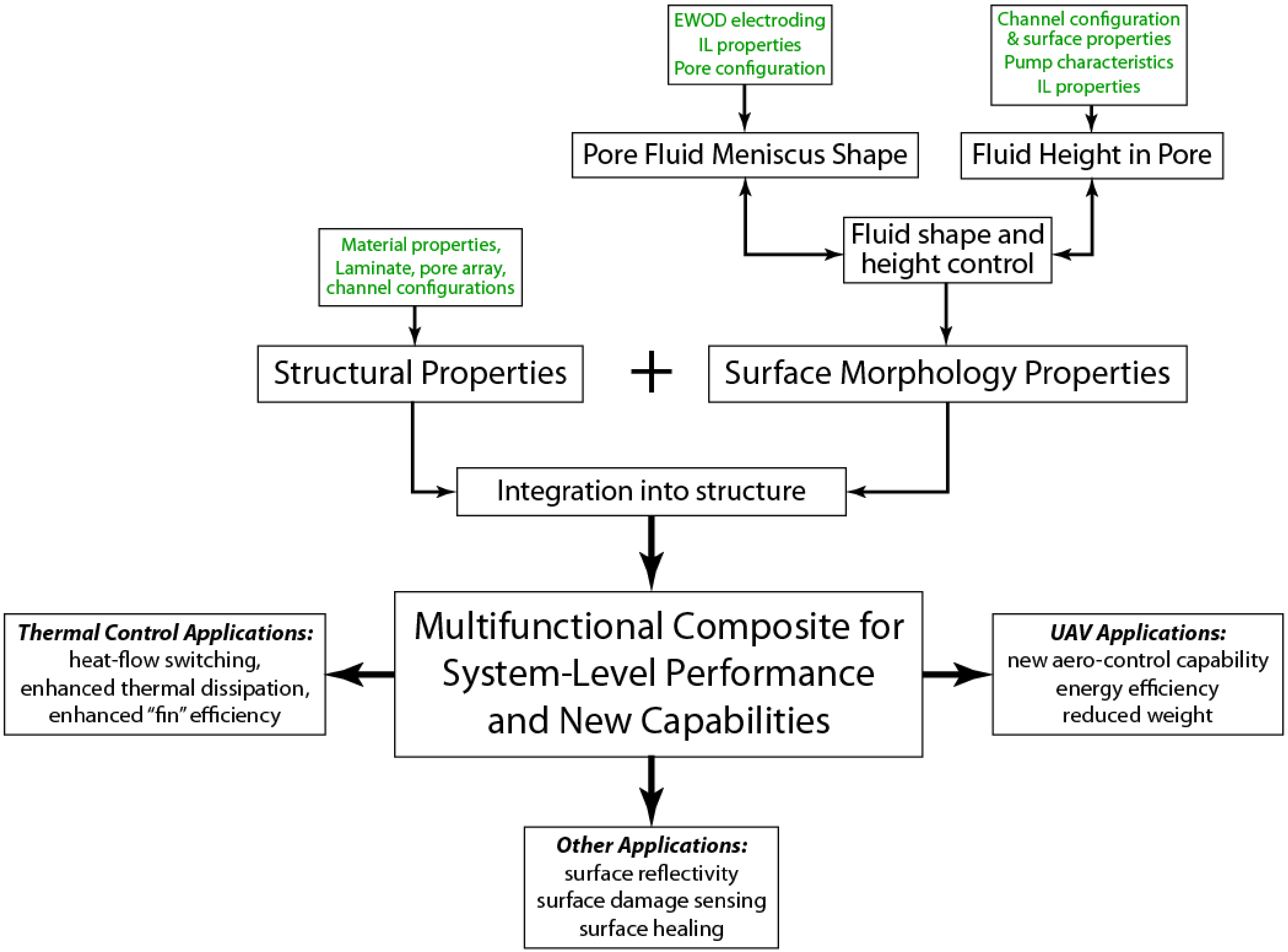
Adapted from: J. D. Anderson, *Introduction to Flight*, 3rd Ed., McGraw-Hill, Boston, MA 1989

Surface Roughness Effects

Increased roughness (ε/L) →

- induces transition to turbulent boundary-layer flow at lower *Re*,
- turbulent boundary-layer remains attached → lower pressure drag,
- laminar boundary-layer flow separates → higher pressure drag.

Functional Overview



Fluid-Phase Modeling

Bond Number $$B_0 = \frac{\Delta \rho g d}{\gamma / d}$$

$B_0 < 1 \rightarrow$ gravity negligible

$B_0 \sim 0.1$ PV composites

Can ignore gravity!!

Fluid-Phase Modeling

Laplace-Young:
(capillary physics)

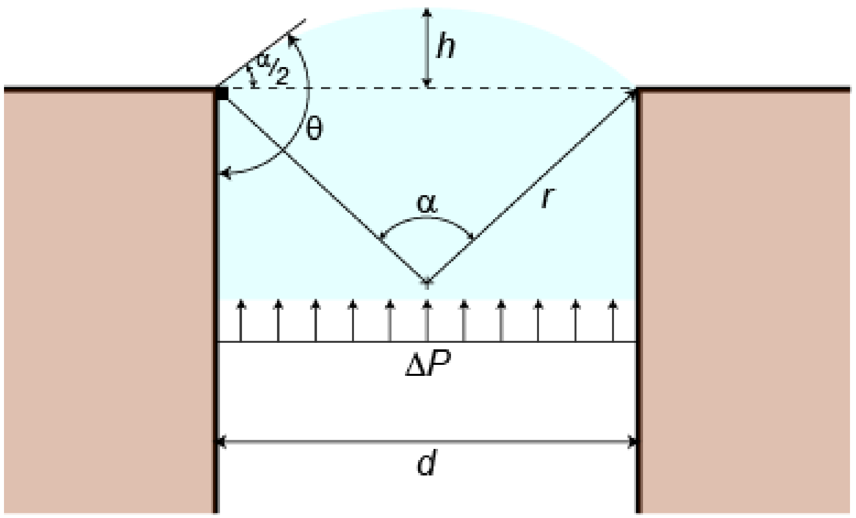
$$\Delta P = \frac{2\gamma}{r}$$

Young-Lippmann:
(EWOD)

$$\cos\theta = \cos\theta_0 + \frac{\varepsilon_0\varepsilon}{2t\gamma}V^2$$

Geometry:

$$r = -\frac{d}{2}\sec\theta$$

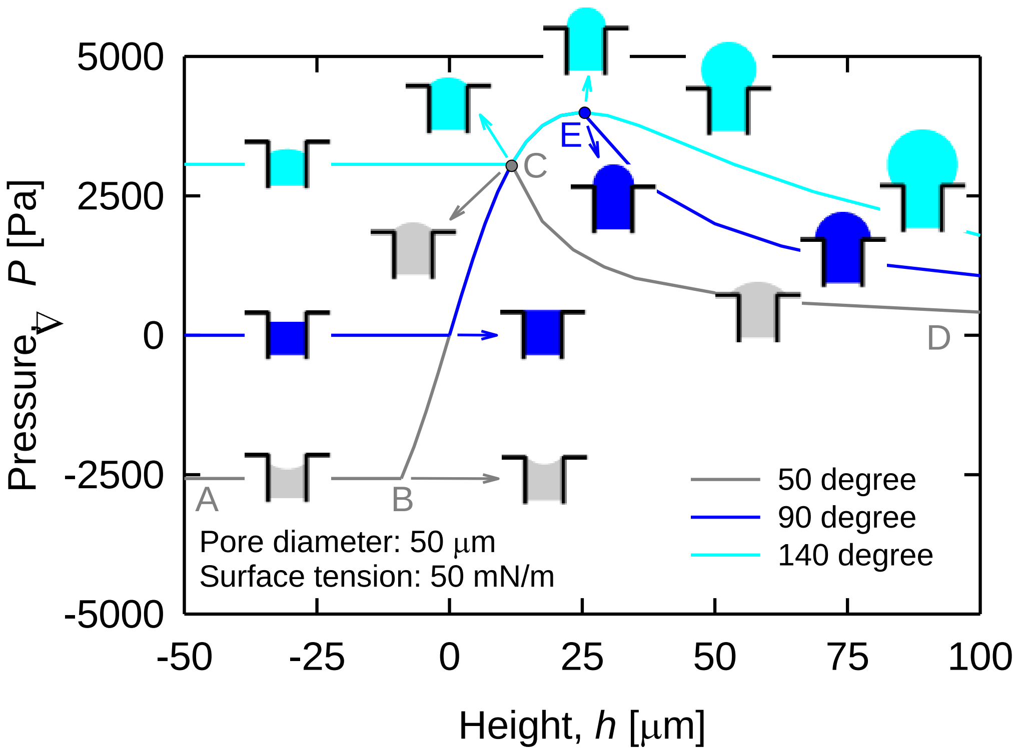


Circular pores → spherical geometry

d = pore diameter
h = distance to meniscus top
θ = contact angle
r = radius of curvature
$\Delta P = p_f - p_a$ = fluid "gauge" pressure

$$\boxed{\Delta P = \frac{-4\gamma}{d}\cos\theta \quad \& \quad h = \frac{d}{2}\left(\frac{\sin\theta - 1}{\cos\theta}\right)}$$

Modeling Results



Key Implications

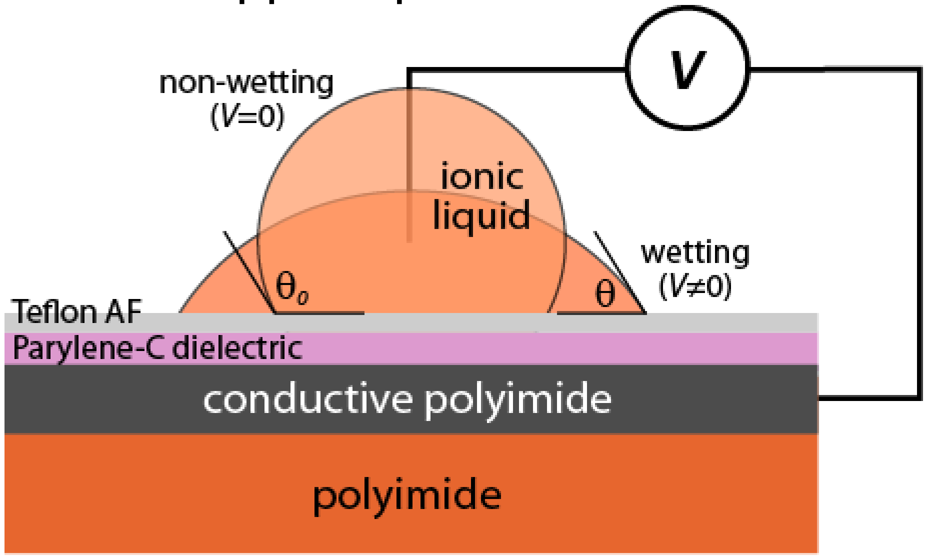
- For stable behavior beyond peak pressure points (e.g., C or E):
  - displacement-pumping avoids uncontrolled spillage from pore,
  - hysteresis prevents siphon from pore with smallest contact angle.
- Large non-wetting contact angle not needed; anything >90 deg OK.
- Domed geometry natural → others (flat or dimple) require polarization.

Three Regimes

1. A-B: pore filling (constant *r* & *p*)
2. B-C: pore-surface transition ($\theta \rightarrow \theta + \pi/2$)
3. C-D: fluid spreading (*r* ↑ & *p* ↓)

Electro-Wetting on Dielectric (EWOD)

Influence of applied potential on contact angle.



Flat EWOD test geometry

Lippmann-Young Equation:

$$\cos\theta = \cos\theta_0 + \frac{1}{2\gamma}\left(\frac{\varepsilon_0\varepsilon}{t}\right)V^2$$

Apparent contact angle

Intrinsic contact angle (zero voltage)

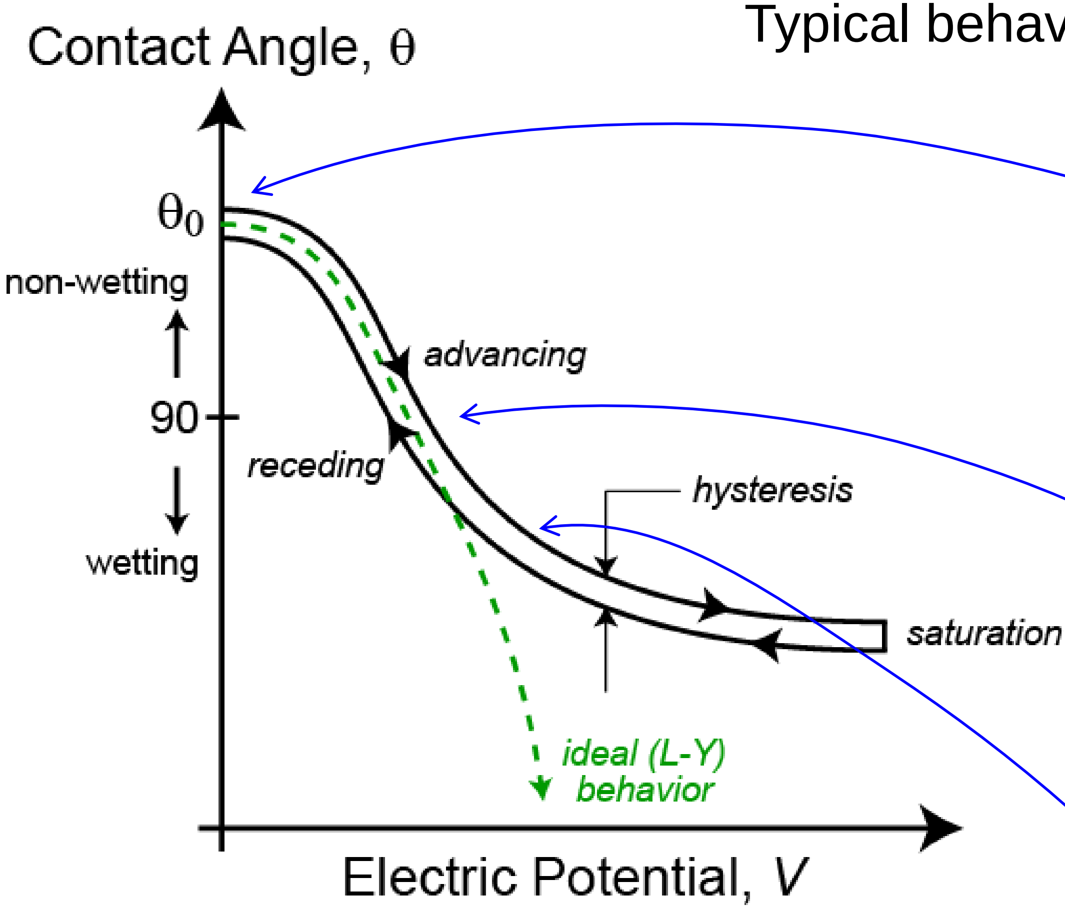
Interfacial tension (IFT) of ionic liquid

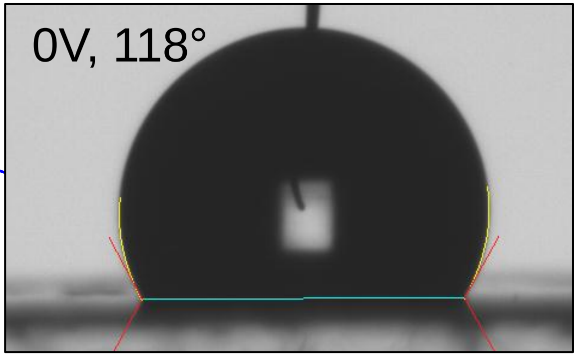
Permittivity of dielectric layer(s) over thickness

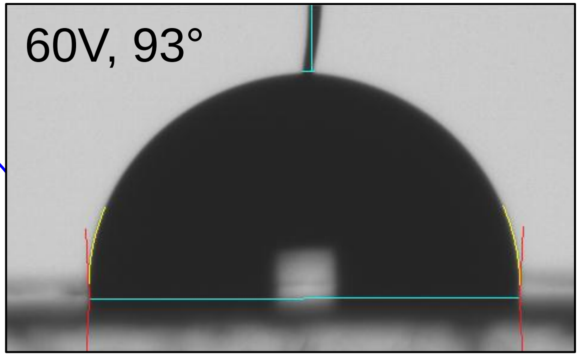
Applied potential

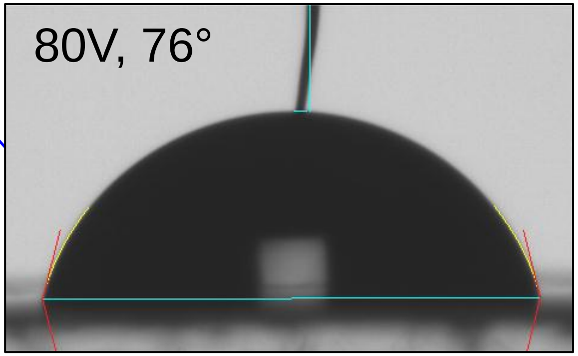
Electro-Wetting on Dielectric (EWOD)

Typical behavior







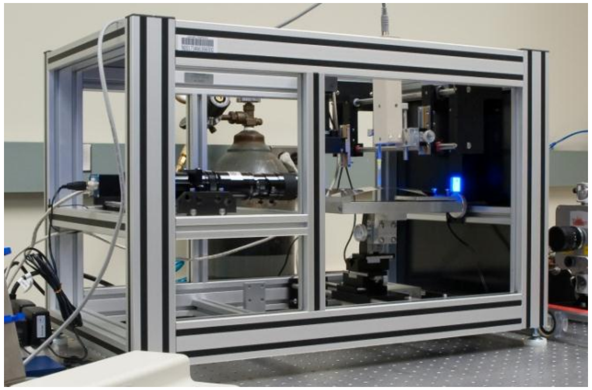


Design Objectives:

- maximal $\Delta\theta$ with V
- minimal hysteresis

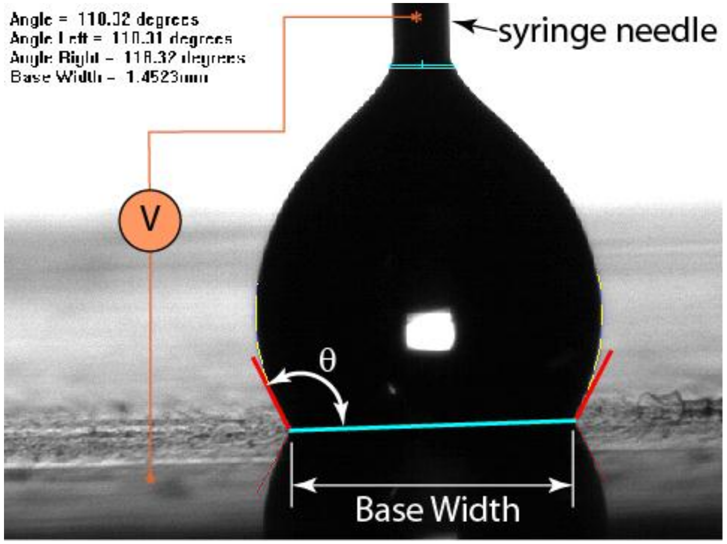
EWOD and Meniscus Characterization

flat plates → single (capillary) pore → PV pore arrays

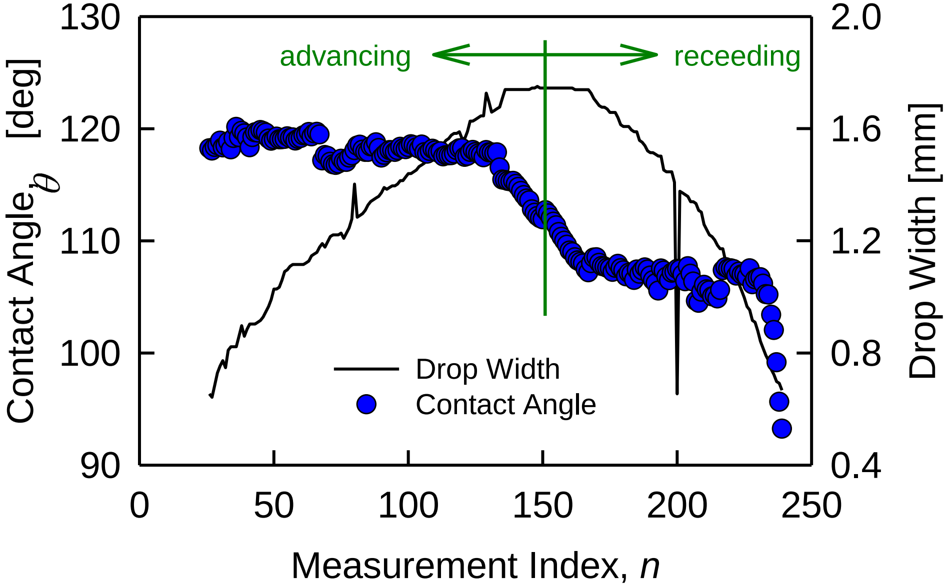


FTA 1000 Drop-Shape Characterization

- Microscope lens: 0.5 to 12x magnification
- Side-, top-view cameras to 60 frames/sec



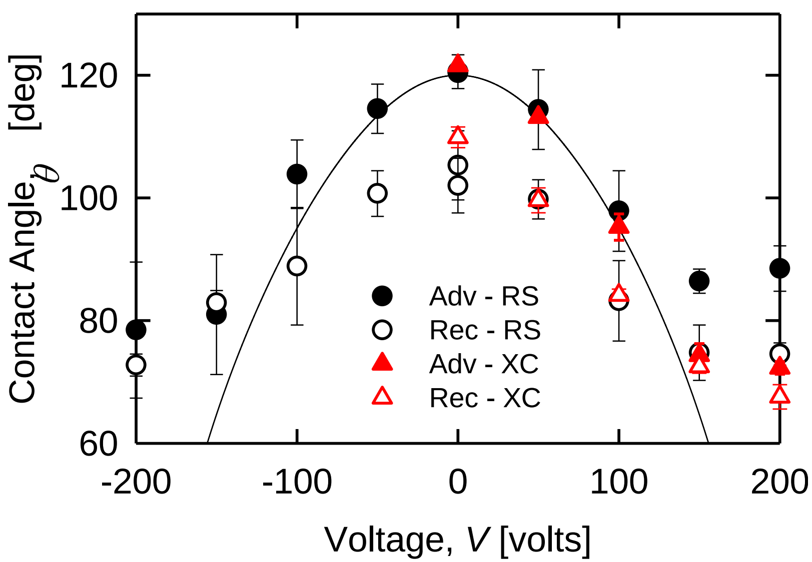
EWOD Characterization Procedure



Aqueous 0.1 M NaCl Solution
Conductive Kapton XC substrate
Parylene-C (5.0 um) dielectric
Teflon AF 1600 (200 nm) hydrophobic
Applied potential: 0 (±50, 100, 150, 200) volts

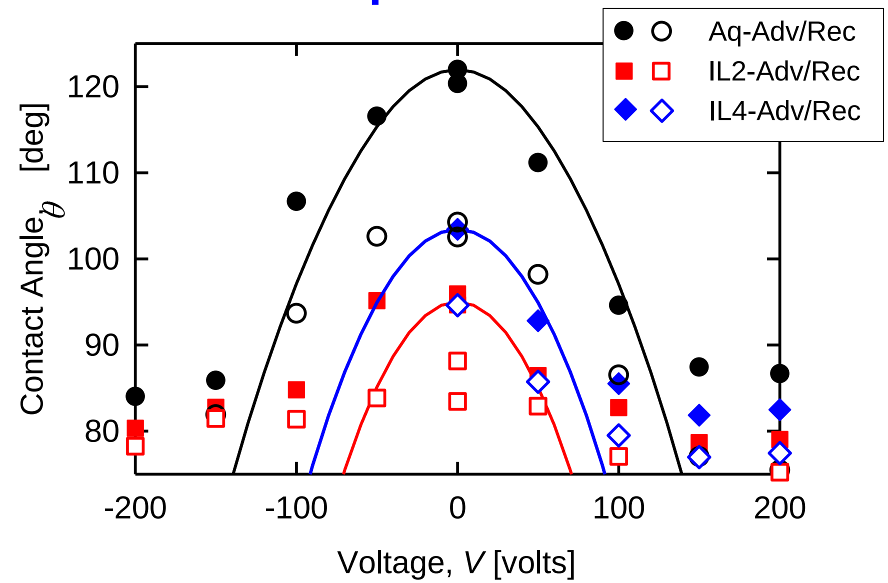
Flat Plate EWOD Characterization

Substrate Effects



Aqueous 0.1 M NaCl solution
Conductive Kapton RS or XC substrates
Parylene-C (5.0 um) dielectric
Teflon AF 1600 (200 nm) hydrophobic

Fluid Composition Effects

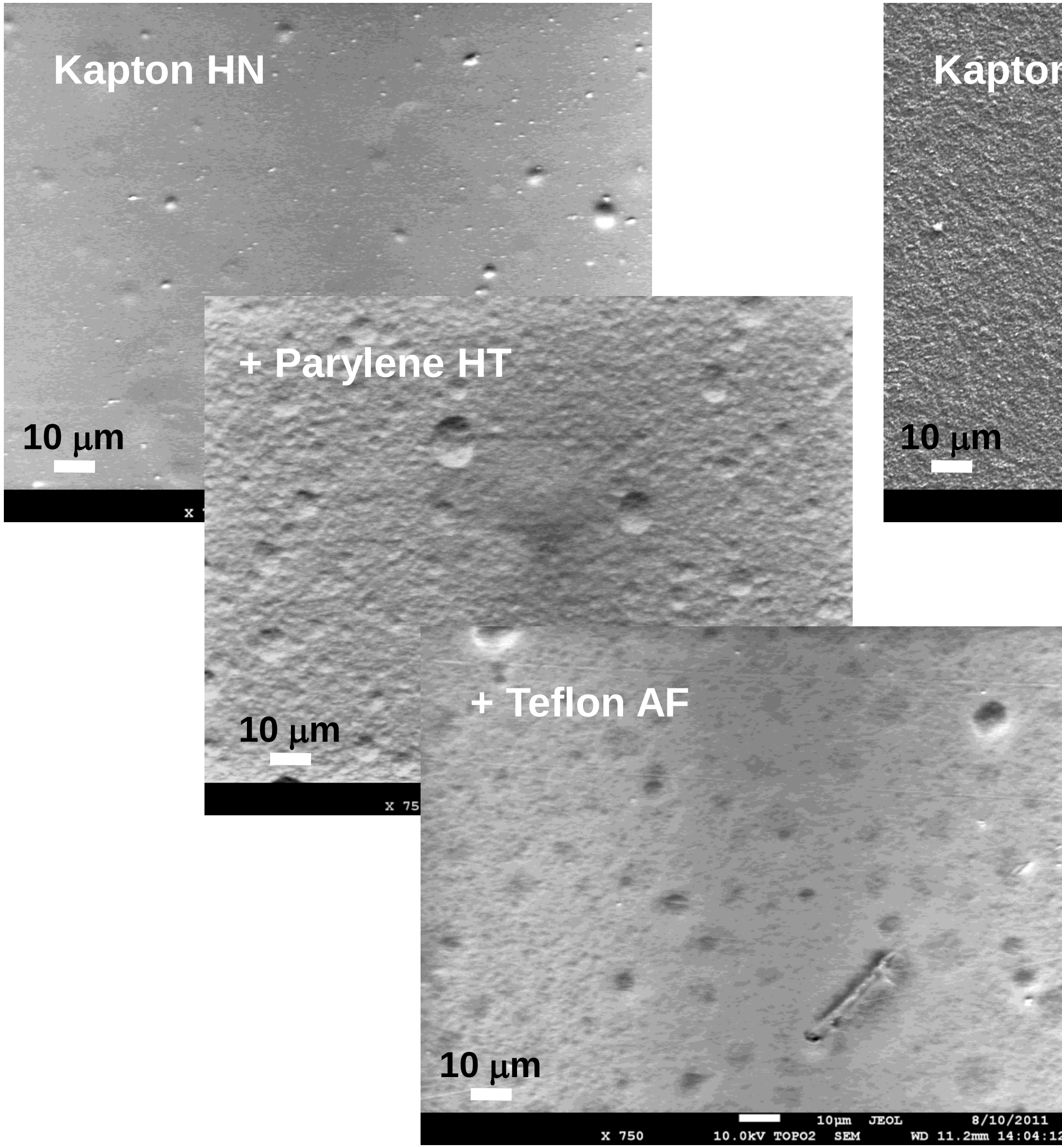


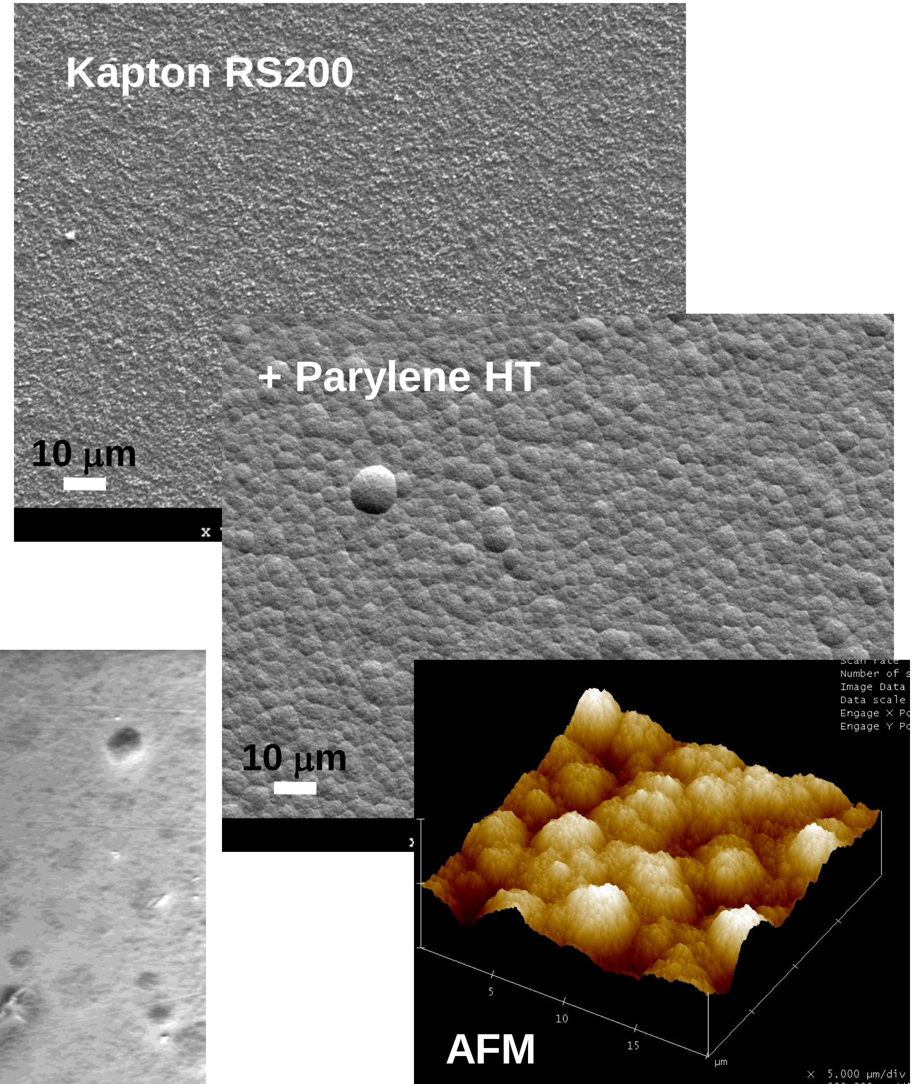
Aqueous: 0.1 M NaCl solution
IL2: 1-Ethyl-3-methylimidazolium acetate
IL4: 1-Ethyl-3-methylimidazolium methyl sulfate
Conductive Kapton RS substrate
Parylene-C (5.0 um) dielectric
Teflon AF 1600 (200 nm) hydrophobic

Key Implications

- Aqueous (0.1 M NaCl) fluids show larger $\Delta\theta$ versus applied potential,
- $\Delta\theta$ hysteresis due to variations in surface electrode layer properties.

Layer Deposition Effects



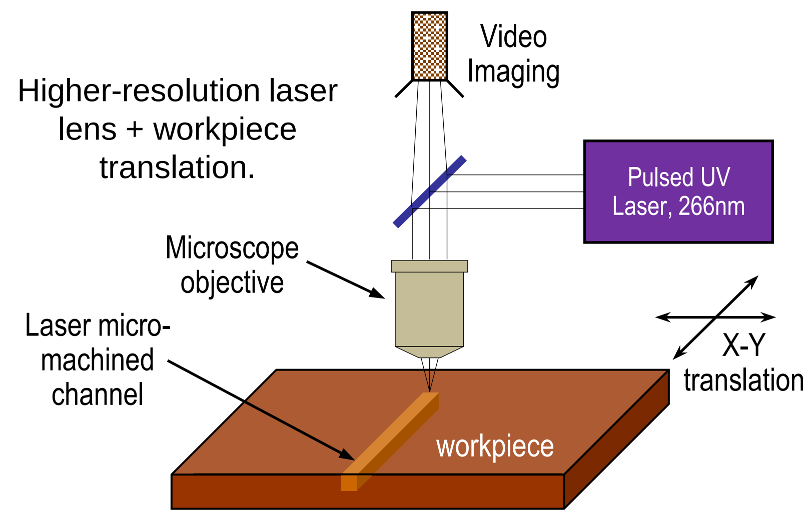


$(\Delta h)_{max}$ ~ 600 nm

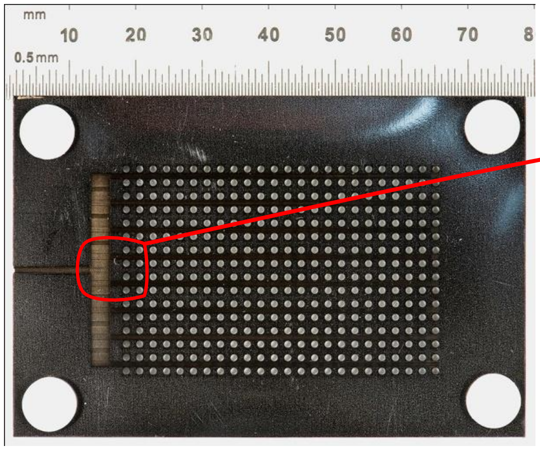
Fabrication

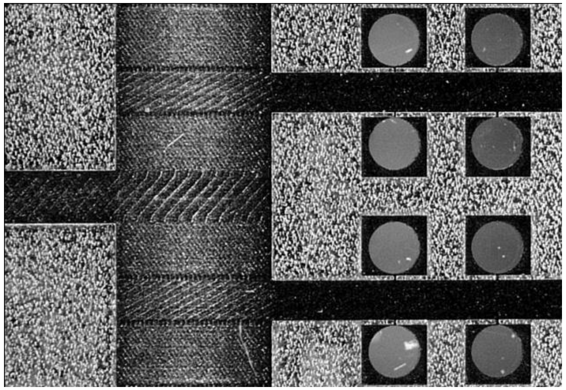
- **EWOD experiments:**
  - Flat specimens for electroding and IL shape control studies.
  - Glass capillary “single-pore analogs” for meniscus shape control studies.
- **PV composites experiments:**
  - Non-functional prototypes for fabrication technique assessment.
  - Functional PV composite prototypes for fluid control and pumping demonstrations.

Laser Micromachining System



Higher-speed possible via laser raster with stationary workpiece.





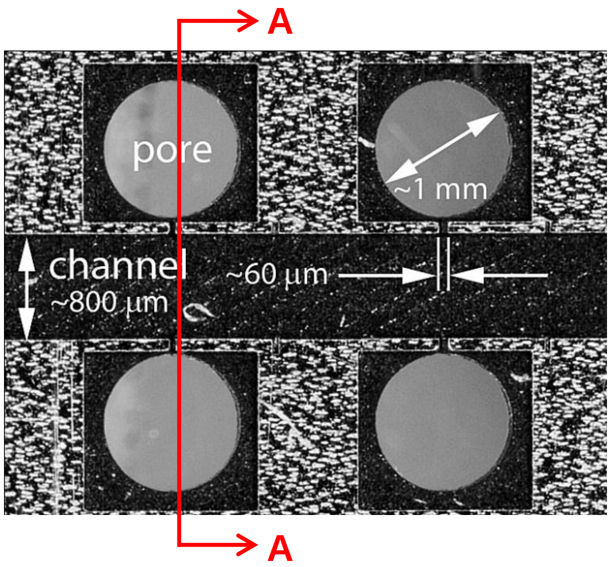
PV Composite Prototyping

5-Layer Laminate Design

Section A-A

Processing Steps:

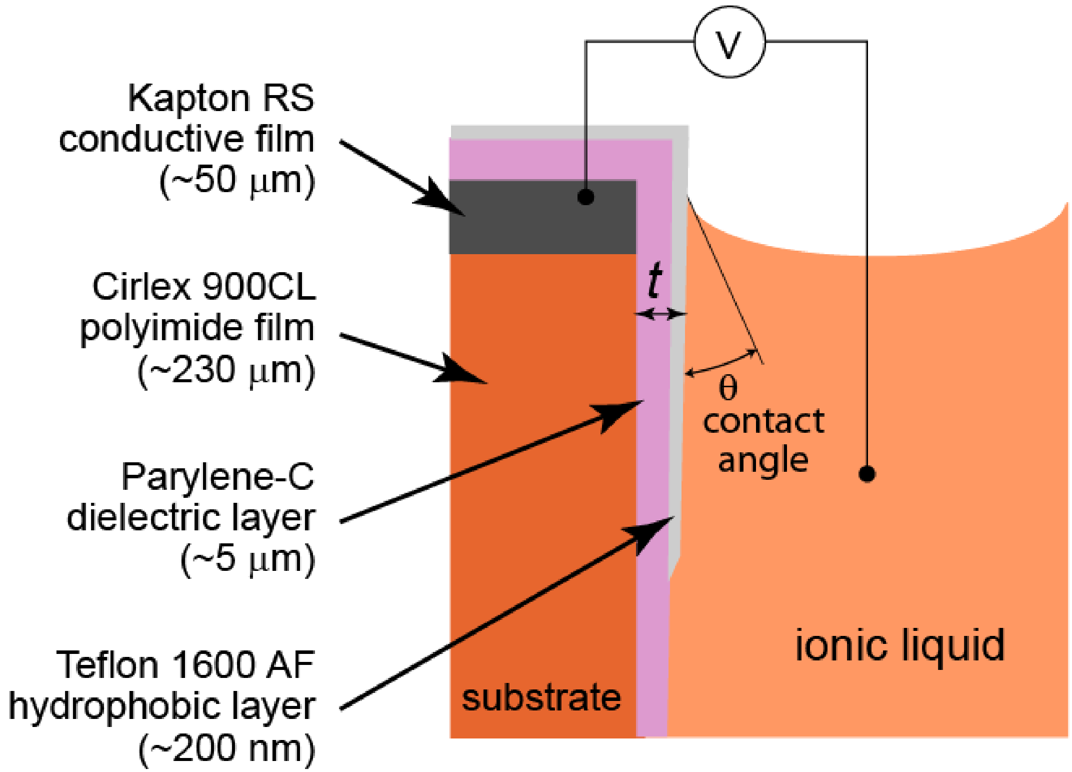
- Kapton RS bonded to Cirlex then laser micro-machined to create pores and channels,
- Glass capillary bonded to main channel for external-fluidic connection,
- Kapton HN bonded to seal channels,
- Assembly vapor-coated with Parylene-C and spin-coated with Teflon AF.



EWOD Electroding in PV Composites

Materials; thicknesses; and processing challenges

Pore Cross-Section

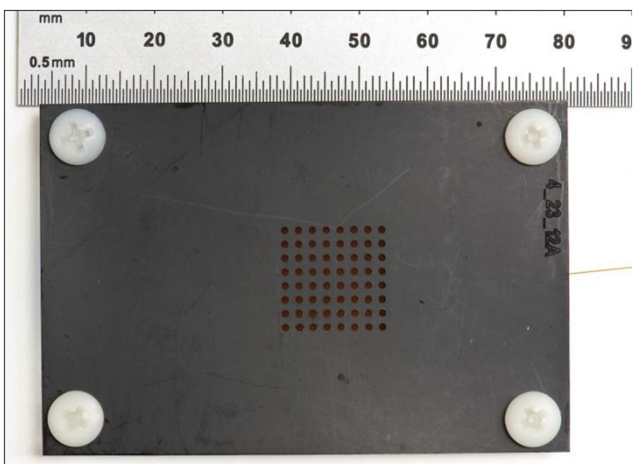


Key Challenges

- Require EWOD electroding on pore walls and surface at exit;
- Must avoid conductive paths between IL and solid-phase.

Fluid Height Control in Pores

- **Objective:** assess uniformity of fluid filling of pores.
- **Setup:** poro-vascular prototype without electroding layers:
    - 1000 μm diameter pores, 8 x 8 array,
    - external displacement pump control,
    - water, isopropyl alcohol fluids.
- **Measurements:**
    - qualitative video



Results

- Fluid constrictions at pore entries allowed uniform fluid delivery to all pores in array,
- Vascular designs with appropriate fluid curvatures needed via channel-pore geometry and surface coatings to assure uniform delivery.

Ongoing and Future Work

- Fluid shape-height control and characterization:
  - EWOD experimentation with glass capillaries ("single-pore") and pore-array configurations,
  - Particle additives in fluid for enhanced EWOD performance,
  - Vascular network design for filling and fluid height control in pore,
- Structural characterization and interactions:
  - Mechanical properties,
  - Deformation interactions with fluid control,
- Application to airfoil aerodynamics:
  - Wind-tunnel experiments with "static" silicone PVC models on airfoil geometry for drag, lift, and transition characterization and proof-of-concept,
  - Computational simulation of surface morphology effects on boundary layer flow using airfoil models and direct numerical simulation,
  - Computational modeling/design to determine optimal surface morphologies for airfoil control applications.